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Superconducting phase tuned sample-specific conductance fluctuations

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Abstract

We have studied sample-specific conductance fluctuations tuned by the phase difference between superconducting boundaries attached to a T-shaped two-dimensional electron gas. In low magnetic fields, oscillations due to phase-conjugated Andreev reflections were observed with an amplitude $\delta G_{qp} \simeq 0.10e^2/h$. These oscillations were suppressed by a flux of approximately h/e through the interference region. For larger magnetic fields, superconducting-phase modulated sample-specific conductance fluctuations were found with an amplitude $\delta G_{\Delta\phi} \simeq 0.005e^2/h$.

Keywords: Universal conductance fluctuations (UCF); Superconductors; Interferometers

We present a study of the sensitivity of sample-specific conductance fluctuations to boundary conditions imposed by a superconductor. For a single normal–superconductor (NS) junction, the conductance fluctuations (UCF) are expected to remain universal with a magnitude $\delta G \approx 2e^2/h$ [1]. These UCF can be studied in an SNS-interferometer by changing the phase difference between the superconductors [2], since Andreev reflected holes and electrons receive the macroscopic phase of the superconductor [3]. Weak localization due to interference between time-reversed electron–hole trajectories, inducing an $h/4e$ period, is predicted in SNS-interferometers with a separation between the superconductors larger than the thermal length ξ_T ($\approx \sqrt{\hbar D/k_B T}$) [4].

We have designed an interferometer by coupling an interrupted superconducting loop to a T-shaped two-dimensional electron gas (2DEG) (see Fig. 1). The phase difference between the superconductors can be controlled by an applied magnetic flux. The 2DEG was confined into a narrow channel in order to decrease the number of quantum channels. This makes it possible to investigate conductance fluctuations of the order of e^2/h or smaller. Also spectroscopy up to energies above the superconducting gap voltage could be performed without exceeding the critical current of the superconductor.

We used an InAs/AlSb heterostructure, because of the absence of a Schottky barrier between the superconductors and the 2DEG in the 15 nm InAs layer underneath. The 40 nm AlSb top layer was removed prior to processing. Patterning of the 2DEG was done by wet etching using conventional e-beam lithography. The transport properties of the 2DEG in a wet-etched InAs channel were $n_s \simeq 2.5 \times 10^{16}\,m^{-2}$ and $\mu_e \simeq 0.8\,m^2\,V/s$, resulting in an electron mean free path $l_e \simeq 0.2\,\mu m$. The 50 nm Nb superconducting electrodes were deposited after in situ Ar cleaning of the exposed InAs surface. The length L of the T-shaped 2DEG between the Nb electrodes is 0.7 μm

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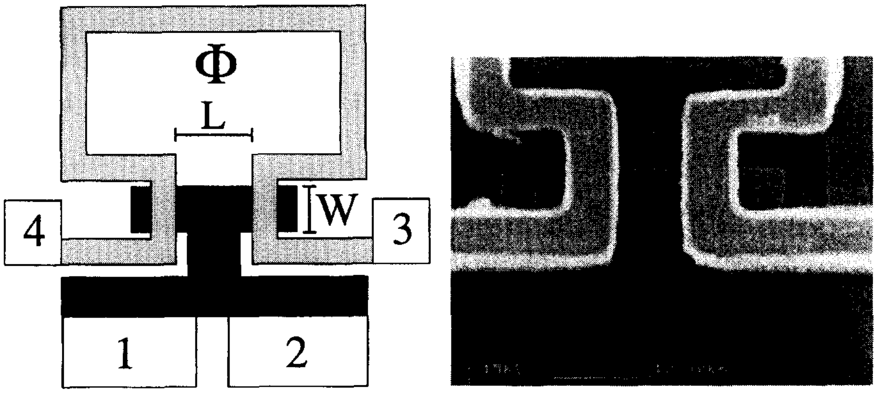

Fig. 1. Sample layout. The left-hand panel shows a schematic picture of the T-shaped 2DEG with the interrupted niobium loop. The contacts (1) and (2) are connected to the T-shaped 2DEG and (3) and (4) are connected to the superconducting niobium loop. The dimensions are $L \simeq 0.7$ μm and $W \simeq 0.3$ μm. The right-hand panel shows a SEM micrograph.

and the width W is 0.3 μm, resulting in diffusive transport in this channel. This corresponds with a Thouless energy ($E_T = \hbar v_F l_e / L^2 \simeq 0.3$ meV). We have checked that the Nb loop remained superconducting for all applied magnetic fields. As a consequence, the Nb electrodes had the same electrochemical potential.

We have characterized three devices at a temperature of 50 mK using standard 4-probe AC lock-in techniques with filtered leads. We present the data of one device. The current was injected by one of the contacts (1, 2) and was extracted by one of the contacts (3, 4). The voltage difference was measured between the two remaining contacts. The zero-bias resistance $R_{14,23}$ is approximately 1370 Ω, which corresponds well with a geometrical estimate of four times the square resistance. Furthermore, the energy-dependence of $R_{14,23}$ showed a decrease of 4.5% below 2.0 mV due to the onset of Andreev reflections. The magnitude of the decrease is 20% of the estimated Sharvin resistance, indicating that the NS-interface is indeed highly transparent ($T_{NS} \approx 0.7$) [5]. Since the decrease in the resistance started close to the niobium energy gap ($\Delta_{Nb} \sim 1.3$ meV), the energy-relaxation length l_{in} is at least comparable to the length of the T-shaped 2DEG.

Fig. 2 displays the magnetoresistance. The effect of the applied magnetic field is twofold. First, the phase difference $\Delta\phi$ between the two superconducting electrodes is changed according to: $\Delta\phi = 2\pi\Phi/\Phi_0$, where Φ is the applied flux through area A ($\approx 10.3\,\mu\text{m}^2$) confined by the Nb loop and the T-shaped 2DEG and $\Phi_0 \equiv h/2e$. Second, the magnetic field penetrates the T-shaped 2DEG. Due to the Meissner effect this magnetic field was enlarged by a factor $\sim (L+D)/L$, where D is the width of the Nb wires (≈ 0.5 μm). In the upper panel of Fig. 2(a) the magnetoresistance $R_{14,23}$ at low B is shown. Panel (b) shows a close-up of these low-field quasiparticle oscillations with an amplitude $\delta G_{qp} \simeq 0.10 e^2/h$. The period in magnetic field corresponds within 10% with the geometrical expectation. These quasiparticle interference oscillations are expected to average out, when two flux quanta Φ_0 penetrate the upper part of the T-shaped 2DEG [6]. In our device this occurs at approximately 120 Gauss, which corresponds well with 2 Φ_0 through the upper part of the T-shaped 2DEG (area $\simeq (L+D)W$).

Surprisingly, the oscillations do not completely disappear for magnetic fields corresponding to several flux quanta through the total T-shaped 2DEG, as one can see in panels (c) and (d). The typical amplitude of these high-field oscillations is $\delta G_{\Delta\phi} \simeq 0.005 e^2/h$ and the period is $h/2e$. In Fig. 3(a) the fluctuating background resistance with $\delta G_{UCF} \simeq 0.02\ e^2/h$ is subtracted from the raw data, leaving the $h/2e$ oscillations. The cross-over from low-field quasiparticle oscillations to high-field oscillations around 120 Gauss is evident. The envelope of the high-field oscillations clearly fluctuates. We have analysed the autocorrelation $C(\Delta B)$ of both the high-field

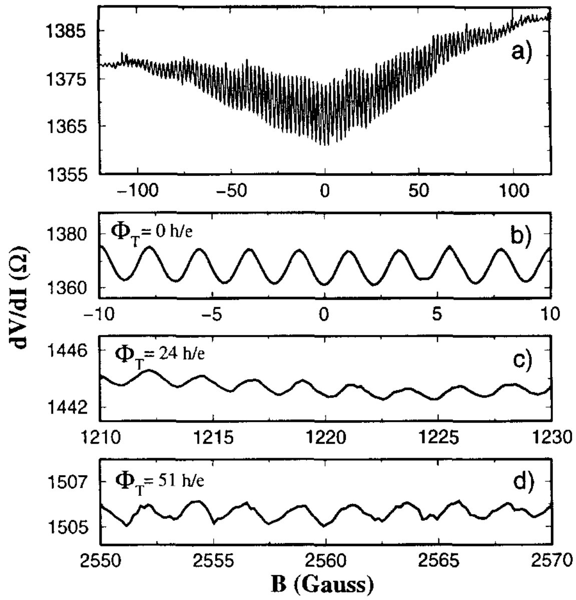

Fig. 2. Panels (a) and (b) display the magnetoresistance $R_{13,24}$ in low magnetic fields, whereas panels (c) and (d) display two traces in higher magnetic fields at $T = 50$ mK. The flux Φ_T indicates the number of flux quanta h/e ($\simeq 50$ Gauss) through the total T-shaped 2DEG including the Meissner effect.

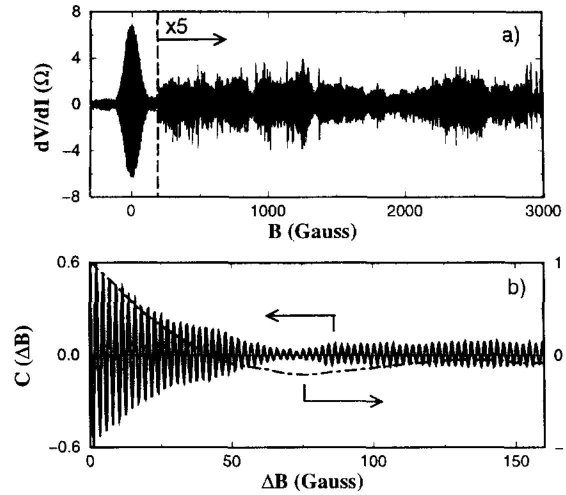

Fig. 3. (a) Magnetoresistance $R_{13,24}$ minus the background resistance at $T = 50$ mK. (b) Autocorrelation function $C(\Delta B) \equiv \langle R(B)R(B+\Delta B)\rangle / \langle R(B)^2\rangle$ between 200 and 3000 Gauss for the superconducting phase tuned conductance oscillations of the trace shown in (a) (solid line) and the correlation function of the fluctuations in the background resistance (dashed line).

oscillations and the fluctuations in the background resistance for $B \geqslant 200$ Gauss (see Fig. 3(b)). A shift in the magnetic flux by an amount h/e through the phase-coherent interference region should reduce the correlation to half of both the high-field oscillations and the fluctuations in the background resistance. This should happen around 50 Gauss. In Fig. 3(b) this occurs around 30 Gauss, which could indicate that the total phase-coherent interference region extends outside the T-shaped 2DEG. Since both the high-field oscillations and the fluctuations in the background resistance show the same decay in the autocorrelation, we attribute these high-field oscillations to be sample-specific conductance fluctuations tuned by the phase difference across the two superconducting boundaries.

The magnitude of δG_{UCF} is lower than expected, which we ascribe to our specific geometry. Furthermore, since $\delta G_{\Delta\phi} \approx 0.25 \delta G_{\mathrm{UCF}}$, we believe that the boundary conditions imposed by the superconductors cannot fully modulate the conductance fluctuations. The other two devices showed a similar behavior at low magnetic fields, but the signatures of both the high-field superconductor-modulated conductance oscillations and the fluctuations in the background resistance were completely different.

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